Fuzzy Logic-Based Automated pH and Temperature Control System for Biofilter in Smart Aquaponics

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Abstract

Aquaponics is a modern agricultural approach that relies heavily on recirculating water between aquaculture and hydroponic units, thus a specialized set of water chemistry is needed to sustain a healthy and functioning aquaponics system. The addition of a biofiltration system helps in converting ammonia, a toxic byproduct of fish metabolism, to nitrates which is the nitrogen form that can easily be utilized by plants. Naturally present nitrifying bacteria need an optimum pH and temperature to maximize the conversion of ammonium to nitrites and nitrites to nitrates. Thus, monitoring and controlling the pH and temperature is needed to maintain a functional aquaponics system. To address this problem, a fuzzy logic-based system is created to control the solenoid valves that will supply additional acid or base and switches for the Peltier cooler and heater for correcting the temperature in the biofilter. Using the Mamdani approach in the fuzzy inference engine, the duration of the opening for the solenoid valves, cooler, and heater were suggested.

***Keywords*—biofilter, biosystem, aquaponics, fuzzy logic controller, pH, temperature**

I. Introduction

Aquaponics is an integrated approach that recirculates the nutrient-rich water from aquaculture for nutrient absorption by plants in the hydroponics units after the microbial conversion of toxic substances to harmless substances [1]. Aquaponics has been receiving significant interest over the past few years as it is considered an innovative solution for food security [2]. Although previous researches have cited aquaponics for further development regarding cost-effectiveness and technical capabilities [2], this approach is still promising particularly to meet food requirements for areas with high urbanization. The recirculating water in the aquaponics system also contains both dissolved organic matter such as ammonia and suspended solids in the form of sludge [3]dill (Anethum graveolens L.. A biofiltration system which composed of settleable solids removal followed by a biofiltration process can be employed to maintain the quality of the water recirculating through the system.

The biofiltration process is governed by two simultaneous reactions converting ammonia to nitrite and nitrite to nitrate [4]. Three main nitrifying bacteria take part in the nitrification process: *Nitrosomonas* which converts ammonia to nitrite as shown in equation 1 and *nitrobacter* and *nitrospira* which convert nitrite to nitrate as shown in equation 2 [5]. These bacteria are naturally occurring in the environment. However, these bacteria need to grow and colonize a medium such as gravel, pumice, plastic, etc. to be effective. To support the growth of these bacteria, key water qualities such as pH and temperature must be monitored and taken into consideration. In general, optimum nitrifying bacteria growth in the biofilter is expected at pH 7.0 to 8.0 [5] and temperature 25 to 30°C [6].

$$NH_4^+ + O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (1)$$

$$NO_2^- + O_2 \rightarrow NO_3^- \quad (2)$$

To maintain optimal and stable growth of fishes and crops in an aquaponics system, it is necessary to monitor and control environmental parameters such as temperature and pH [7]. The main objective of this study is to design

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an automated control system for maintaining the pH and temperature of the water in the biofilter to support the optimum conversion of ammonia to nitrite and nitrite to nitrate. Specifically, the goal is to implement a fuzzy logic system to regulate the pH and temperature of the water in the biofilter tanks. The input parameters of the system are pH and temperature while the output will be the controls of solenoid valves for the acid and the base to maintain the pH level and controls for the Peltier cooler and Peltier heater to maintain the temperature of the water.

II. Water Parameters and Filtration Process

A. Water Quality Variable: pH and Temperature

Power of Hydrogen (pH) is considered as the "master variable" for aquaponics system because it influences many other water parameters including the ratio of toxic to nontoxic ammonia in aqueous solutions and the rate of nitrification by nitrifying bacteria in the biofilter [8]. Thus, monitoring pH level is significant because it declines normally due to nitrification and fish respiration [5][8]. If the pH level is low, the rate of nitrification declines resulting in the accumulation of ammonia in the recirculating water making the environment toxic to the fishes. The pH level can drop to as low as 4.5 where no nitrification occurs and total ammonia nitrogen (TAN) can ascent to as high as 30 parts per million (ppm). Normal TAN level should be maintained at less than 1 ppm [8]. The gradual addition of calcium (Ca^{2+}) and potassium (K^{+}) can be implemented to increase the pH. If the pH is high, recirculating water can have a relatively high level of water hardness. Water hardness refers to the concentration of divalent metal ions usually calcium (Ca^{2+}) and magnesium (Mg^{2+}) [9]. Denitrification which is manifested in plateauing or increasing pH levels can be an indication of an anaerobic (oxygen-free) condition in the aquaponics system [8]. Removing accumulation of organic matter can be implemented to remediate the situation.

The temperature of the water not only affects the fishes but also the growth of the plants and the performance of the nitrifying bacteria [8][10]. Biological reaction rates such as the nitrification process increase with the increase in temperature until an optimal temperature is reached [11]mathematical modeling and sensitivity analysis. The results show that the impact of temperature on fixed film nitrification rate is less significant than that predicted by the van't Hoff-Arrhenius equation. In a fixed film biofilter, the impact of temperature on nitrification rate due to DO (dissolved oxygen. Beyond the optimum temperature, reaction rates will continue to decline. However, the dissolved oxygen content of the water is higher in lower temperatures as the solubility of oxygen in water decreases with rising temperatures [6].

B. Biofiltration System

In a typical aquaponics system, the biofiltration system is composed of two different processes: mechanical filtration where removal of settleable solids happens, and the biofiltration process where the biological process of converting toxic nitrogenous waste to nontoxic nitrate occurs [12]. Mechanical filters are situated before biofilters to reduce the chances of the settleable solids breaking down into smaller particles which are more difficult to treat and consume more oxygen [5]. Small organic particles can also clog the roots of the plants. Biofilters are usually a tank, barrel, or drum that is heavily aerated and contains porous media such as sand, gravel, pumice, and bioplastics. The tank and porous media provide the nitrifying bacteria enough area to colonize, and with proper temperature, pH, and dissolved oxygen level, optimum nitrification is expected [13].

C. pH and Temperature Monitoring and Control Systems

Water plays a vital role in the aquaponics system, thus it must be kept at an optimal condition to support a high productivity rate for both fish and plant units [14]. The developed system can measure and control the pH level, temperature, and dissolved oxygen using Raspberry Pi as network backbone. Arduino microprocessors send data to a central node that hosts a local server for storing data. The control system can run actuators manually by the user or automatically as a response to the parametric changes in the sensors. The network backbone hosts a website where data is displayed and updated every half second. A web application is also created to display sensor logs and manually control the actuators anywhere [10].

A wireless sensor network (WSN) is implemented in aquaponics to effectively reduce the complexity of the working environment, and high wiring costs. The system used a core CC2530 that follows the Zigbee protocol and uses the fuzzy PID control algorithm to process and improve the accuracy of the test data [15].

Internet of Things (IoT) is also one of the most promising technology that offers a lot of innovative solutions that can be applied to aquaponics systems [16]. IoT– based applications that can be accessed through smartphones are developed for real-time monitoring and controlling of the aquaponics system [17][18][19]. The source node, which was the data collector and sender, consists of a microcontroller, water level sensor, temperature sensor, pH sensor, ammonia gas sensor, peristaltic motor, servo motor, and aquaponic coolant and heater or Peltier element. The control parameter data will be used to respond to the system. If the temperature is low, the system will activate the heater. Vice versa, if the temperature is high, the coolant will be activated. If the pH level is beyond optimum level, the system will actuate the peristaltic motors of H_3PO_4 or KOH, depending on if the system needs more acid or base [18].

III. Methodology

As shown in Fig. 1, the biofiltration system is composed of two main processes: mechanical filtration and the biofilter. Mechanical filtration is used to separate suspended solids and fish feces [7]. The settling basin type of clarifier is used for mechanical filtration. A settling basin is usually a long rectangular tank a couple of feet long and a few inches deep [12]. As the water enters the basin, solid particles settle at the bottom at the basin. Water will overflow at the other end of the tank with fewer particles suspended in the water.

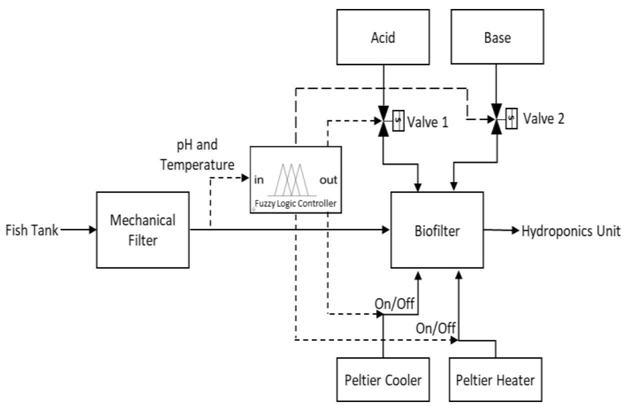

Fig. 1. Design of the pH and Temperature Control System

For the biofilter design, sand filtration is used due to its design simplicity, basic handling procedure, and low maintenance cost [20]. The sand filter serves a dual purpose for the water: removes suspended solids and provides a large surface area for biological degradation [20]. The first layer of the biofilter is the sand then followed by gravel at the bottom of the tank. The specific surface area for coarse sand can reach up to 100 m^2/kg [21] and 0.05 to 0.389 m^2/kg depending on the grain size [22]a system for dry farming has evolved based on the employ of gravel mulch. A couple of lab experiments were conducted to study the influences of mulch stratum thickness and gravel grain size on water vapor flow, with a focus on resistance to evaporation in gravel mulch stratum. In Experiment 1, six treatments included mulching with gravel of different thickness (2. cm, 4. cm, 6. cm, 8. cm and 10. cm. As shown in Fig. 2, the water from the mechanical filter will enter from the top and will pass through a diffuser plate. The diffuser plate will serve as the protection of the sand from being disrupted due to the force of the water being poured into the filter. The electrode sensor for pH sensing and thermocouples for temperature sensing is placed in the middle of the sand medium.

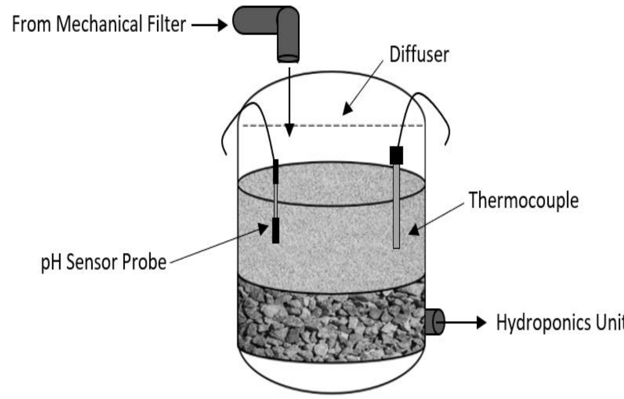

Fig. 2. Sand Biofilter Design

B. Fuzzy Logic Modelling

Automation aids humans to have real-time supervision of every process to come up with the desired output. Fuzzy control gives a proper methodology for representing, manipulating, and implementing a human's reasoning or knowledge about how to control a system. Fuzzy logic was used in a study evaluating an electronic nose for the quality classification of tomato puree using ammonia and methane concentrations as inputs [23]. In swarm robotics, the fuzzy logic controller was used to minimize the distance between the robot agents, thus mitigating the effect of aerodynamic drag and resulting in a more efficient formation configuration [24]. Fuzzy logic is used in this study to control the valves for the acid and base and the switches for the Peltier cooler and heater as shown in Fig. 3.

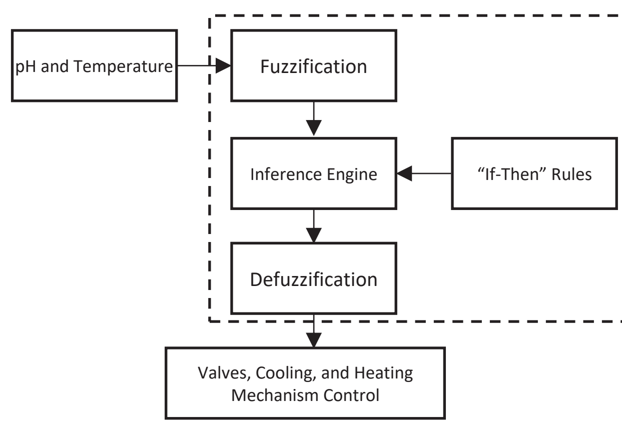

Fig. 3. pH and Temperature Control System using Fuzzy Logic

The crisp inputs for the system are the pH and temperature of the incoming water from the mechanical filtration tank.

The desired outputs are control of the solenoid valves for the acid and base and the switches for the cooling and heating elements. The fuzzy sets using linguistic variables and the term members are defined as well.

pH Level (pH)	=	{low, normal, high}
TempLevel (T)	=	{cold, normal, hot}
Valve1Control (v1)	=	{off, short, long}
Valve2Control (v2)	=	{off, short, long}
CoolerControl (cc)	=	{off, short, long}
HeaterControl (hc)	=	{off, short, long}

The pH parameter is categorized into three linguistic values: low, normal, and high. As shown in Fig. 4, the membership functions can be represented using trapezoidal and triangular functions. The degrees of membership ranges are 0 to 7.0 for low, 7.0 to 8.0 for normal, and 8.0 to 14.0 for high.

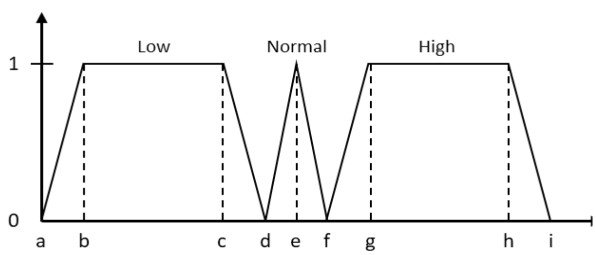

Fig. 4. Membership Function for pH

The pH linguistic values are represented by equations 3, 4, and 5.

$$\mu_{pHlow} = \begin{cases} \frac{x - a}{b - a} & a \leq b \\ 1 & b \leq c \\ \frac{d - x}{d - c} & c \leq d \end{cases} \quad (3)$$

$$\mu_{pHnormal} = \begin{cases} \frac{x - d}{e - d} & d \leq e \\ \frac{f - x}{f - e} & e \leq f \end{cases} \quad (4)$$

$$\mu_{pHhigh} = \begin{cases} \frac{x - f}{g - f} & f \leq g \\ 1 & g \leq h \\ \frac{i - x}{i - h} & h \leq i \end{cases} \quad (5)$$

The temperature parameter is also categorized into three linguistic values: cold, normal, and hot. As shown in Fig. 5, the membership functions are represented using the trapezoidal and triangular functions. The degrees of membership ranges are 0 to 25°C for cold, 25 to 30°C for normal, and 30 to 40°C for hot.

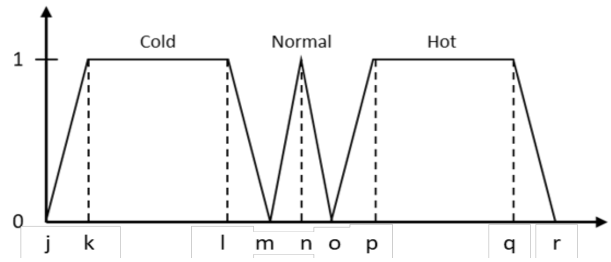

Fig. 5. Membership Function for Temperature

The temperature linguistic values are represented by equations 6, 7, and 8.

$$\mu_{pHcold} = \begin{cases} \frac{x - j}{k - j} & j \leq k \\ 1 & k \leq l \\ \frac{m - x}{m - l} & l \leq m \end{cases} \quad (6)$$

$$\mu_{pHnormal} = \begin{cases} \frac{x - m}{n - m} & m \leq n \\ \frac{o - x}{o - n} & n \leq o \end{cases} \quad (7)$$

$$\mu_{pHhot} = \begin{cases} \frac{x - p}{q - p} & o \leq p \\ 1 & p \leq q \\ \frac{r - x}{r - q} & q \leq r \end{cases} \quad (8)$$

The crisp outputs of the fuzzy logic controller are the valve 1 control for the acid, valve 2 control for the base, switch control for the Peltier cooler, and the switch control for the Peltier heater. As shown in Fig. 6, the membership functions for the controls of valve 1, valve 2, cooler, and heater are represented using triangular functions. The degrees of membership ranges for valve 1 and valve 2 are 0 minute for off, 0 to 2.5 minutes for short, and 1.25 to 5.0 minutes for long. The degrees of membership ranges for the control of the Peltier cooler and the Peltier heater are 0 minute for off, 0 to 1.5 minutes for short, and 1.0 to 4.0 minutes for long.

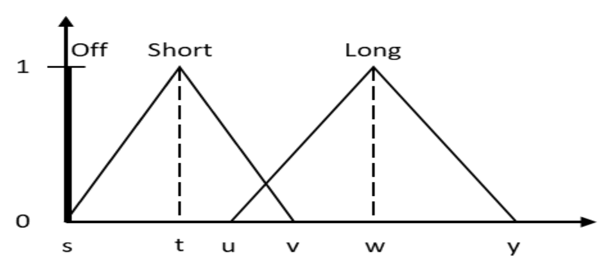

Fig. 6. Membership Function for Valve 1, Valve 2, Cooler, and Heater

The linguistic values for output solenoid valves 1 and 2 are represented by equations 9, 10, and 11. The linguistic values for the output control for the cooler and heater are also represented by equations 9, 10, and 11.

$$\mu_{v1off},\ \mu_{v2off},\ \mu_{ccoff},\ \mu_{hcoff} = s \qquad x \leq s \tag{9}$$

$$\mu_{v1short},\ \mu_{v2short},\ \mu_{ccshort},\ \mu_{hcshort} = \begin{cases} \dfrac{x - s}{t - s} & s \leq x \leq t \\ \dfrac{v - x}{v - t} & t \leq x \leq v \end{cases} \tag{10}$$

$$\mu_{v1long},\ \mu_{v2long},\ \mu_{cclong},\ \mu_{hclong} = \begin{cases} \dfrac{x - u}{w - u} & u \leq x \leq w \\ \dfrac{y - x}{y - w} & w \leq x \leq y \end{cases} \tag{11}$$

To simplify the process, If-Then rules for the input and the output variables were set. A total of 9 rules were defined since there are 3 sublevels per input variable. Table 1 shows the rules defined for the system using AND as an operator for the input variables. For example, Rule 1 is interpreted as IF pH is low AND temperature is cold, THEN valve 1 is short, valve 2 is long, cooler is short, and the heater is long.

Table 1.
Rule-Base for the Fuzzy Control System

If		Then			
pH	Temperature	V 1	V 2	Cooler	Heater
Low	Cold	Short	Long	Short	Long
Low	Normal	Short	Long	Off	Off
Low	Hot	Short	Long	Long	Short
Normal	Cold	Off	Off	Short	Long
Normal	Normal	Off	Off	Off	Off
Normal	Hot	Off	Off	Long	Short
High	Cold	Long	Short	Short	Long
High	Normal	Long	Short	Off	Off
High	Hot	Long	Short	Long	Short

The results of the interference engine are then turned into crisp values using a method known as the center of area or center of gravity (COG). As given by equation 15, this method returns the value of the center of gravity of the curve.

$$X = \frac{\int \mu_A \cdot x \, dx}{\int \mu_A \, dx} \tag{15}$$

The fuzzy logic controller created was simulated using MATLAB Simulink. Mamdani technique was used in the fuzzy interference system in transforming the pH and temperature inputs to outputs for the controls of the valves, cooler, and heater. Fig. 7 shows the Simulink diagram for the control system with pH and temperature as the crisp input and acid valve, base valve, Peltier cooler, and Peltier heater as the crisp output. For the pH values, a sine wave with an amplitude of 7, a bias of 7, and a frequency of 1 rad/sec were created using the sine wave generator. For the temperature values, a sine wave with an amplitude of 20, a bias of 20, and a frequency of 4 rad/sec were created. The pH and temperature inputs were sent through a multiplexer before entering the fuzzy logic controller. The output of the fuzzy logic controller was sent to a demultiplexer where the output was separated into four outputs: valve 1, valve 2, cooler, and heater.

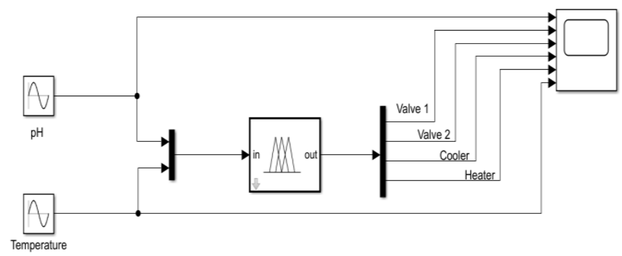

Fig. 7. Simulink Diagram for pH and Temperature Control System

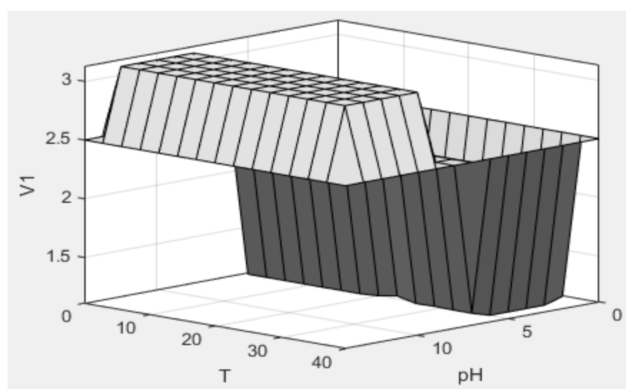

Fig. 8. Valve 1 Feedback to pH and Temperature Input

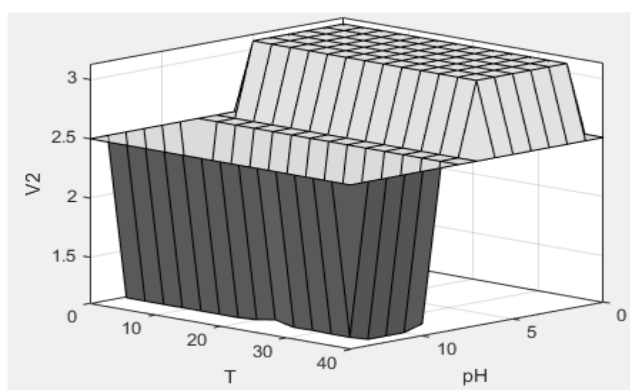

Fig. 9. Valve 2 Feedback to pH and Temperature Input

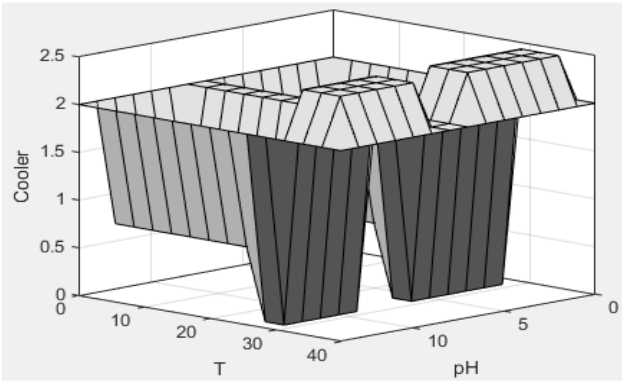

Fig. 10. Peltier Cooler Feedback to pH and Temperature Input

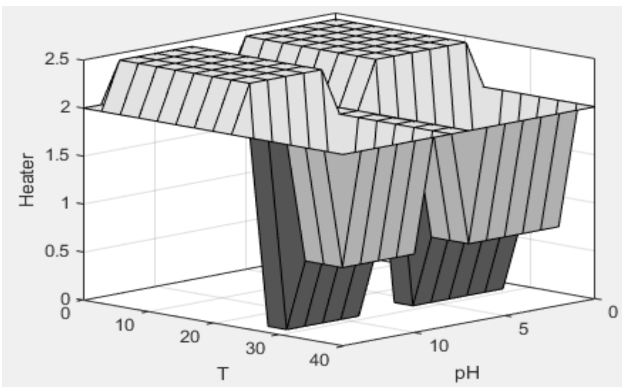

Fig. 11. Peltier Heater Feedback to pH and Temperature Input

Fig. 12 shows all the possible combinations of the pH and temperature which were plotted using sine waves. For example, at time step 0.5, the pH level is 11 and the temperature 38°C. In linguistic variables, the pH is HIGH while the temperature is HOT. Based on Fig. 13, the response of the system is 3.2 minutes for Valve 1 which LONG in the linguistic variable, 1.2 minutes for Valve 2 which is SHORT, 2.5 minutes for the cooler which is LONG, and 0.7 minutes for the heater which is SHORT. At time step 3.1, the pH is 7 which is NORMAL, and the temperature is 17°C which is COLD. The response of the system is 0 minutes for valve 1 and valve 2 which is OFF, 0.8 minutes for cooler which is SHORT, and 2.5 minutes for the heater which is LONG. At time step 3.5, the pH is 5 which is LOW, and the temperature is at a maximum of 40°C which is HOT. The response of the system is 1.2 minutes for valve 1 which is SHORT, 3.1 minutes for valve 2 which is LONG, 2.5 minutes for cooler which is LONG, and 0.7 minutes for the heater which is SHORT.

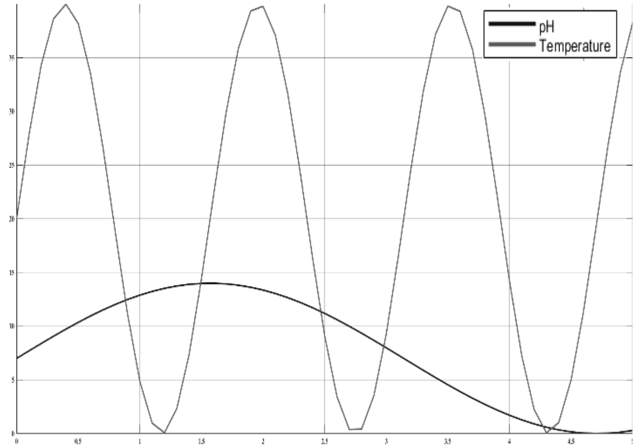

Fig. 12. Simulation Duration vs. Input Parameters

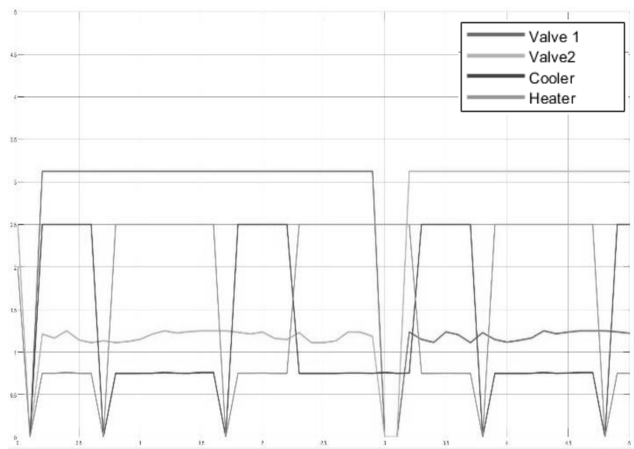

Fig. 13. Simulation Duration vs. Output State

V. Conclusion and Recommendation

This study presented a practical design for biofilter and an automated pH and temperature control system based on fuzzy logic approach. For the biofilter system, a settling basin type of clarifier was used due to its practicality and ease of use. For the biofilter, the porous media used was sand and gravel due to it s large specific surface area where nitrifying bacteria can colonize. As for the fuzzy logic model, pH and temperature were used for the crisp inputs while the duration of the controls for the solenoid valves for acid or base addition and switches for the Peltier cooler and heater were decided. This control system helped in supporting the optimum pH level and temperature for biological degradation of the harmful ammonium compounds to harmless nitrates.

For further researches related to this study, real-time monitoring of ammonia, nitrites, and nitrates concentrations may be considered to real-time effects of the pH and temperature adjustments.

Acknowledgment

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